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Corn stover harvest changes soil hydrology and soil aggregation

Jane M.F. Johnson[a,*], Jeffrey S. Strock[b], Joel E. Tallaksen[c], Michael Reese[c]

[a] USDA-Agricultural Research Service, North Central Soil Conservation Research Laboratory, 803 Iowa Ave, Morris, MN 56267, United States
[b] University of Minnesota—Southwest Research and Outreach Center, Lamberton, MN 56152, United States
[c] University of Minnesota—West Central Research and Outreach Center, Morris, MN 56267, United States

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ABSTRACT

In the United States, commercial-scale cellulosic-ethanol production using corn (*Zea mays* L.) stover has become a reality. As the industry matures and demand for stover increases, it is important to determine the amount of biomass that can be sustainably harvested while safe-guarding soil quality and productivity. Specific study objectives were to measure indices of soil hydrological and aggregate stability responses to harvesting stover; since stover harvest may negatively impact soil hydrological and physical properties. Responses may differ with tillage management; thus, this paper reports on two independent studies on a tilled (Chisel field) and untilled field (NT1995 field). Each field was managed in a corn/soybean (*Glycine max* [Merr.]) rotation and with two rates of stover return: (1) all returned (Full Return Rate) and (2) an aggressive residue harvest leaving little stover behind (Low Return Rate). Unconfined field soil hydraulic properties and soil aggregate properties were determined. Hydrological response to residue treatments in the Chisel field resulted in low water infiltration for both rates of residue removal. In NT1995 field, Full Return Rate had greater capacity to transmit water via conductive pathways, which were compromised in Low Return Rate. Collectively, indices of soil aggregation in both experiments provided evidence that the aggregates were less stable, resulting in a shift toward more small aggregates at the expense of larger aggregates when stover is not returned to the soil. In both fields, aggressive stover harvest degraded soil physical and hydrological properties. No tillage management did not protect soil in absence of adequate residue.

1. Introduction

In the United States corn (*Zea mays* L.) stover is the most abundant crop residue. Historically, unless harvested as animal feed or bedding, crop residues were returned to the land (Johnson et al., 2006). On the land, crop residues provide surface cover, raw materials for building soil organic matter, and contribute directly and indirectly to aggregate formation (Blanco-Canqui et al., 2007; Pikul et al., 2009; Six et al., 2000), which in turn may interact with soil hydrological properties (Benjamin et al., 2008; Rawls et al., 2004) and other soil properties (e.g., Benjamin and Karlen, 2014; Blanco-Canqui and Lal, 2009; Johnson et al., 2011; Lal and Stewart, 2010). In 2014, commercial cellulosic-ethanol production became a reality (http://poet.com/pr/first-commercial-scale-cellulosic-plant), which at least locally will increase the demand for cellulosic feedstocks and may result in potential environmental risk and soil degradation unless carefully managed to avoid over-harvesting (Archer and Johnson, 2012). Negative impacts on soil properties will impede society's ability to meet the expanding global demand for food, feed, fiber and fuel (Andreev et al., 2013).

As demand for stover or other crop residue increases to meet emerging (i.e., energy) and historical (animal bedding or other uses) needs, it becomes increasingly critical to have a clear understanding of how reducing the rate of crop residues remaining in the field impacts soil properties. Management without tillage and aggressive stover harvest reduced particulate organic matter, increased the erodible-sized dry aggregates, and left the soil surface exposed to erosive forces compared to returning all stover (Johnson et al., 2013). Harvesting stover can impact soil hydrological properties negatively because of changes in physical characteristics, such as reduced porosity and aggregation (Blanco-Canqui and Lal, 2009; Cibin et al., 2012; Osborne et al., 2014), and

Abbreviations: ASW, aggregates from a class-size that remain stable in water; DASD, dry aggregate size distribution; EF, erodible fraction; MWD, mean weight diameter.

* Corresponding author.
E-mail address: jane.johnson@ars.usda.gov (J.M.F. Johnson).

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increased surface sealing or crusting (Blanco-Canqui and Lal, 2009). As reviewed by Blanco-Canqui and Lal (2009) and by Johnson et al. (2010), less stover on the soil surface can impact soil microclimate increasing soil temperature and evapotranspiration; thus, if coupled with less infiltration crop production could be adversely impacted during periods of limited rainfall.

A key factor for increasing agricultural production, related to stover harvest, is proper soil and water management (Hatfield and Sauer, 2011; Westfall et al., 2010). The process of water infiltration through surface soil under rain-fed conditions is a complex interaction among precipitation intensity, soil type, surface condition, and extent that soil is covered by crop residues (Langhans et al., 2011). Retaining corn stover or wheat straw improved water infiltration in both tilled and no-till fields (Govaerts et al., 2007), while low residue return resulted in an increased risk for run-off (Wienhold et al., 2011). Literature reviewed by Blanco-Canqui and Lal (2009) noted conflicting impacts on water filtration in response to residue cover related to interaction among tillage, soil profile characteristics, and water repellency. Conservation practices including reduced or no tillage can increase soil coverage, provided residues are not aggressively harvested (Baumhardt et al., 2012). However, conservation or no tillage practices may not avoid a loss of soil quality when stover is aggressively harvested (Stewart et al., 2015).

In the United States, national estimates of how much residue biomass may be sustainably harvested typically assumed that the land would be managed without tillage (Graham et al., 2007; Perlack et al., 2005; US DOE, 2011). In northern states such as Minnesota, no-tillage management has not been extensively adopted (Johnson et al., 2005) because of farmers' concerns regarding crop productivity. Therefore, this paper reports results from two independent studies that were established in 2005, one on a field managed with tillage (Chisel field) and a second field without tillage since 1995 (NT1995 field). The long term objective of this research is to provide producers with tools to answer the question "How much biomass can be sustainably harvested from a given field while still maintaining soil quality and productivity?" The specific objectives addressed were to measure indices of soil hydrological and aggregate stability responses to harvesting stover. Implications and importance of hydraulic and soil physical properties and their interactions in regards to water and erosion will be discussed.

2. Materials and methods

2.1. Site description and characterization

The study was conducted on two fields (Chisel and NT1995) at the Swan Lake research farm near Morris, MN (45°41′N, 95°48′W). This area is characterized by cold winters and warm summers; mean temperature in January and July, −13.1 °C and 21.7 °C, respectively, thirty year (1971–2000) mean precipitation is 645 mm (NOAA-NCDC, 2002). Soils were formed on till plains and moraines from Des Moines Lobe deposited during the Wisconsin glaciations. Based on USDA-SCS (1971) soil maps as previously described by Johnson et al. (2013), three replicates of the Chisel field were on Barnes soils (Fine-loamy, mixed, superactive, frigid Calcic Hapludoll), and the fourth replicate was on an Aastad (Fine-loamy, mixed, superactive, frigid Pachic Hapludoll). All four replicates in the NT1995 field were mapped as Barnes soil.

In 2005 similar, but independent stover harvest studies (details on harvest treatments and mechanism are described in Section 2.2) were established on adjacent fields (~0.5 ha). These fields differed in tillage management and are referred to as Chisel and NT1995 fields (Johnson et al., 2013). For at least 10 years prior to establishment, both experimental fields had been planted to continuous corn or a corn/soybean rotation. Every year and field, both crop phases of the corn/soybean rotations were present such that each field had two crops, four harvest treatments, and four replications for a total of 32 (6 m × 15 m) plots. Within each experiment, replicates were arranged in a randomized complete block design. Those plots planted to corn in 2005 were subjected to stover return treatment in odd-years, with the balance having stover harvested during the corn phase in the even-numbered years. Therefore, in 2012 when these soil hydrological measurements were made, those in corn during odd-numbered years had been subjected to four stover-harvest cycles, while those in corn during even-numbered years had three stover-harvested cycles.

2.1.1. Chisel field

Beginning in the fall of 2005 the Chisel field was managed with annual autumn chisel plowing (≈20 cm) and one or two disk passes (≤15 cm) in the spring to prepare the seedbed (Johnson et al., 2013). Prior to 2005, the field was managed with annual autumn inversion tillage using a moldboard plow.

2.1.2. NT1995 field

As the name NT1995 implies this field has been managed without tillage since 1995, providing a site to study the effect of stover harvest rate in an established no-till field. This is useful because the "Billion Ton Report" based harvest rates on the assumption that fields would be managed without tillage (Perlack et al., 2005). Since 2005, disturbance has been limited to knife injected fertilizer (~6 cm).

2.2. Corn stover harvest rate treatments

Both the Chisel and the NT1995 fields had similar corn stover treatments initiated in the fall of 2005, as described by Johnson et al. (2013). Only data from plots representing the two harvest extremes will be presented: the control in which only corn grain was harvested and all the corn stover was returned >7 Mg ha^{-1} (Full Return Rate) and an aggressive harvest resulting in <2 Mg ha^{-1} (Low Return Rate) stover left in the field. Return rate was determined by collecting corn stover remaining after harvest in a known area. From 2005 to 2008, in the Low Return Rate treatment stover was removed using a single-row flail-knife forage harvester cutting as close to the soil surface as possible. Since 2009 when a one-pass combine designed to improve the efficiency of harvesting corn grain and material other than grain (Isaac et al., 2006) became available, it has been used for subsequent harvests. This one-pass combine returned similar amount of residue but reduced harvest time compared to the forage harvester. Total stover yield was determined from a 1.5 m^2 area at physiological maturity, and was reported as dry mass per area based on oven-dried (60 °C) to constant mass. Grain yield was based on harvest with a two-row plot scale combine, and is presented at 15.5% standard moisture.

2.3. Soil properties

2.3.1. Soil baseline parameters

In both fields, baseline (2005) soil samples were collected using a hydraulic probe to 100 cm as recommended by Liebig et al. (2010). Three soil cores were taken per plot, and were divided into six increments (0–5, 5–10, 10–20, 20–30, 30–60, and 60–100 cm). One core was used for determining soil bulk density at intervals below 10 cm. In the surface 0–5 and 5–10 cm increments, a hand-held soil probe was used to collect a sample for bulk density. Soil texture was determined using the hydrometer method (Day, 1956; Page et al., 1986). Soil pH (1:1 $CaCl_2$) (Thomas, 1996), total C (LECO TRU-SPEC CN analyzer; LECO Corporation, St. Joseph, MI), and inorganic C (Wagner et al., 1998) were determined. Percent soil covered at planting was determined using intercept method (Laflen et al., 1981; Richards et al., 1984).

2.3.2. Unconfined field soil hydraulic properties

Obtaining soil hydraulic properties representative of field soil conditions is an important step in understanding the dynamic processes of water distribution, availability, storage, and loss in the soil. Tension infiltrometers are useful instruments that offer a simple and relatively rapid means of estimating soil hydraulic properties and structural characteristics based on infiltration measurements in the range near saturation. From circular source infiltration experiments, using tension infiltrometers, both the in-situ unsaturated hydraulic conductivity [$K(h)$] and sorptivity (S) of an undisturbed soil (Ankeny et al., 1991; Perroux and White, 1988; Smettem and Clothier, 1989) can be determined. In addition, it is possible to use properties measured during infiltration to characterize the magnitude of the pore size that is hydraulically active (White and Sully, 1987) in drawing water into the soil at an imposed water tension.

Unconfined field soil hydraulic properties were measured using a 0.20 m disk tension infiltrometer (Soil Measurement Systems, Tucson, AZ, USA) on the soil surface. Data were collected between July 6 and August 8, 2012 in both study fields. Each field had 64 tension infiltrometer measurements (four replications, two crops, two residue return treatments, and four surface soil water pressure potential heads). For each measurement, a level soil surface was prepared in non-traffic, inter-rows with care to avoid smearing the soil surface and potentially blocking the pore system. Major surface irregularities and residue were carefully removed. When present, irregularities only occupied a minor area of the infiltration zone; therefore, removal treatments did not interfere with or alter tension infiltrometer measurements. A 1–3 mm layer of moist silica sand was applied in a circular area the same diameter as the tension infiltrometer to improve hydraulic contact between the disk membrane and the soil surface. Steady-state infiltration rates were measured in-situ at the same position, in order to minimize the effects of spatial variability.

An ascending sequence of surface water pressure potential heads (h_o) were chosen: 120 mm (h_{-120}), 60 mm (h_{-60}), 30 mm (h_{-30}), and 15 mm (h_{-15}). Four different surface water pressure potentials were used in order to determine $K_{(h)}$ by pairwise analysis of unconfined infiltration rate data according to the method of Ankeny et al. (1991). Duplicate flux measurements were made for the different supply surface water pressure potential heads. All the measurements were concentrated in a small area of 2 m^2. The surface hydraulic conductivity, $K_o = K(h)$ (LT^{-1}), and the sorptivity, $S_o = S(h)$ ($LT^{-1/2}$), where (h) (L) is capillary pressure head of water at the soil surface, were obtained using the single-disk, multiple-head method described by Ankeny et al. (1991). This method is based on the Wooding (1968) equation for the steady-state asymptotic flux.

Steady-state was determined by recording the drop in water column height in the tension infiltrometer reservoir per unit time. The rate of water flow out of the infiltrometer water supply reservoir and into the soil was manually recorded at 15–120 s intervals depending on the rate of change in the reservoir.

The upper boundary condition at the soil surface was a pressure head boundary condition, in which the pressure head is set at a specified value and can be, defined as:

$$h(z,t) = h_{-p}(t) \; z = 0 \tag{1}$$

where the water potential h (L) at the soil surface, z, was set to a constant value (h_{-p}) corresponding to the tension applied to the tension infiltrometer. Volumetric water content (j) ($m^3\,m^{-3}$), was determined using a ML3 ThetaProbe soil moisture sensor (Dynamax, Inc., Houston, TX). Immediately prior to infiltrometer measurement, initial volumetric water content, j_n, was determined by taking triplicate measurements in close proximity but outside the point of infiltrometer measurements. Immediately after removal of the infiltrometer from the point of measurement duplicate final volumetric water content, at h_{-15}, was measured from the soil surface under the disk.

2.3.3. Aggregate distribution and stability

Dry aggregate size distribution (DASD) and percentage by mass of those aggregates that remain stable in water were used as indicators for a soil's resistance to erosive forces (i.e., wind and water). After moving aside crop residues, surface soil (~0–5 cm) was collected using a shovel as previously described (Johnson et al., 2013; Osborne et al., 2014). These soil samples were air-dried for a minimum of two weeks. A rotary sieve operating at 6-rpms separated about 2 kg soil into aggregate size groupings: 0–0.5, 0.5–1.0, 1.0–2.0, 2.0–3.0, 3.0–5.0, 5.0–9.0, and 9–20 mm; based on the method described by (Chepil, 1962; Pikul et al., 2009). The total mass of aggregates with a diameter >20 mm and the mass of each size-class was determined. Erodible fraction defined as the mass fraction of soil mass <1.0 mm in diameter was calculated similar to Osborne et al. (2014). Mean weight diameter was calculated to estimate the average soil aggregate size (van Bavel, 1950 Youker and McGuinness, 1957) of the aggregates <9 mm. It was calculated as the sum of the products of mean diameter X_i of each size-class fraction and the fraction of the mass W_i for each corresponding fraction (Kemper and Rosenau, 1986).

$$\mathrm{MWD} = \sum\nolimits_{i=1}^{n} XiWi \tag{2}$$

Only for NT1995 field, the fraction of soil within a dry stable aggregate size-classes (0.5–1.0, 1.0–2.0, 2.0–3.0, 3.0–5.0, or 5.0–9.0) that remained stable in water was determined using protocol described by Kemper and Rosenau (1986). Briefly, a 4-g sample of a given dry stable aggregate size-class was placed on a 250 μm sieve. The sieves with dry soil aggregates were dipped mechanically into water for 5 min ± 5. Soil remaining on sieve after dipping was dried at 70 °C to avoid damaging the sieves. Soil

Table 1
Base line soil properties of two near-by fields collected fall 2005.

	Chisel					NT1995				
cm	Bulk density $Mg\,m^{-3}$	pH_{CaCl2}	Sand $g\,kg^{-1}$	Clay	Organic C	Bulk density $Mg\,m^{-3}$	pH_{CaCl2}	Sand $g\,kg^{-1}$	Clay	Organic C
0 to 5	1.26	6.79	360	280	24.8	1.37	6.06	430	230	27.5
5 to 10	1.29	6.77	350	280	22.3	1.41	6.27	420	240	20.4
10 to 20	1.25	6.77	360	230	24.1	1.44	6.48	410	220	20.6
20 to 30	1.42	6.88	340	240	20.4	1.51	6.73	390	220	14.9
30 to 60	1.41	7.58	360	270	6.58	1.41	7.46	420	210	6.60
60 to 100	1.53	7.76	410	250	1.03	1.58	7.73	430	210	1.30

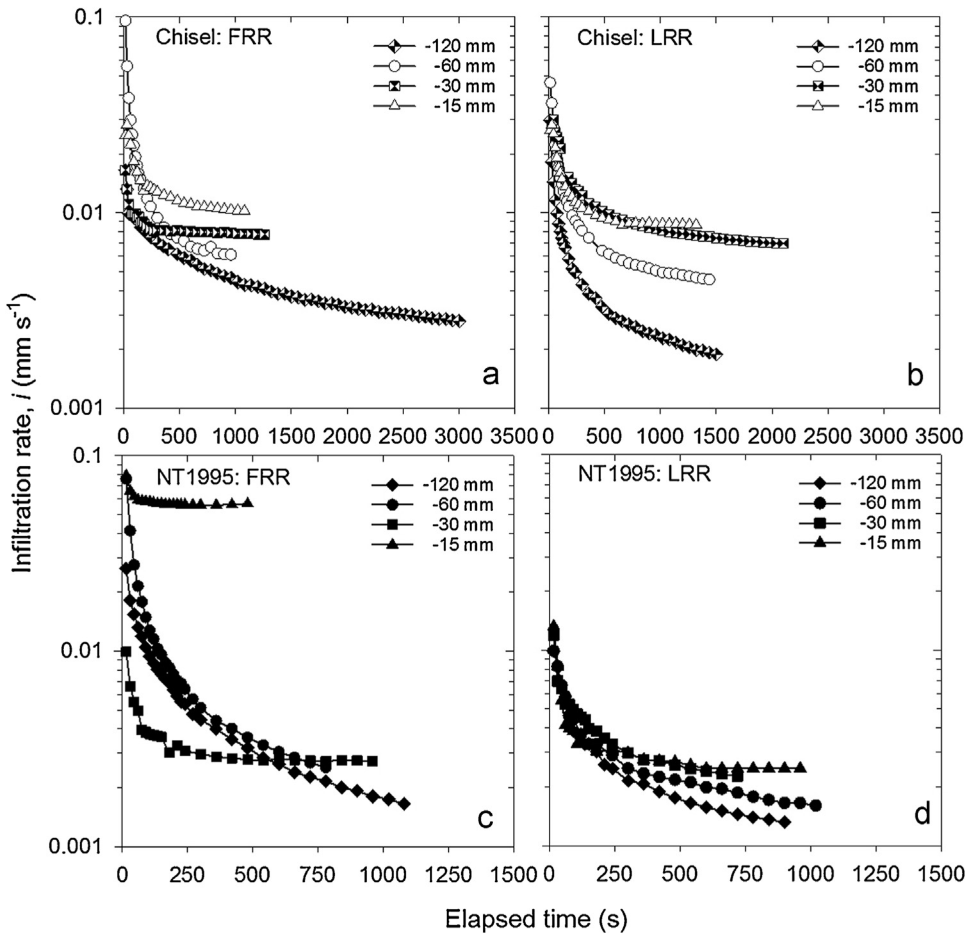

Fig. 1. Example of variation of the infiltration rate with the change in surface water pressure potential observed for a chisel plow tillage system (Chisel) and a no-till system (NT1995). Full Return Rate (FRR) and Low Return Rate (LRR).

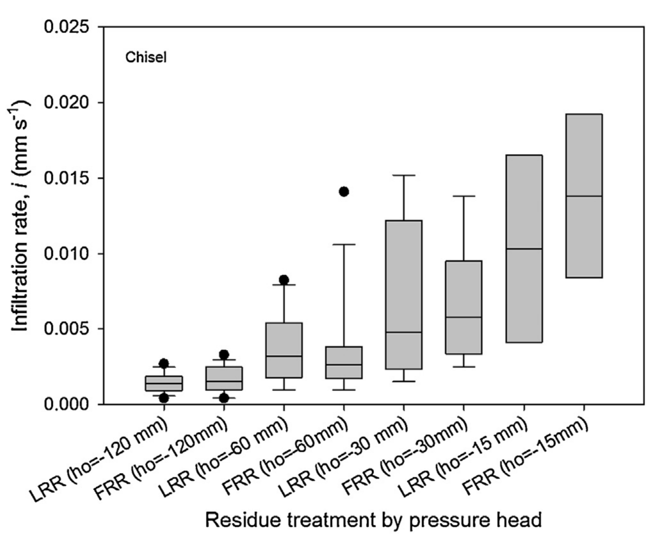

Fig. 2. Effect of residue management, Full Return Rate (FRR) or Low Return Rate (LRR), on the distribution of infiltration rates at four levels of surface water pressure potential (h_o). The horizontal black bar inside the box represents the median infiltration rate for a chisel tillage system (Chisel). The bottom of the box and the top of the box represent the 25th and 75th percentiles, respectively. Lines extending vertically from the box represent variability outside the lower and upper quartile range and numerically represent the 10th and 90th percentiles, respectively. Data points outside the bottom 10% or above the top 90% are plotted as individual closed black circles.

remaining on the sieve corrected for sand mass represents the mass of aggregates stable in water (ASW).

$$\text{ASW g kg}^{-1} = \frac{\textit{mass remaining on the sieve} - \textit{sand mass}}{(\textit{total mass} - \textit{sand mass})} \times 1000 \qquad (3)$$

2.4. Statistical analysis

Replicates were randomized for each field; therefore; independent general linear model analyses compared treatments by field using Proc GLM SAS 9.4 software (SAS Institute, 2012). Significance level is noted when $P \leq 0.1$. Box and whiskers plots were used to visualize data distribution, display the median, 10, 25, 75 and 90% percentiles, and outliers (SAS Institute, 2012).

3. Results

3.1. Stover yield and percentage soil coverage

Yield and stover return rates 2005 through 2011 were reported previously by Johnson et al. (2013). Briefly, in the Chisel field residue return treatments had similar annual average yields for corn (10 Mg ha^{-1}) and soybean (3.3 Mg ha^{-1}). All soybean residue (4.3 ± 1.4 Mg residue ha^{-1} yr^{-1}) was returned. During the corn phase, Full Return Rate averaged 7.97 ± 0.25 Mg stover ha^{-1} yr^{-1} returned, while the Low Return Rate treatment averaged 1.72 ± 0.16 Mg stover ha^{-1} yr^{-1} return. At planting in the Chisel field, the percentage of soil covered with residue was <20% even in

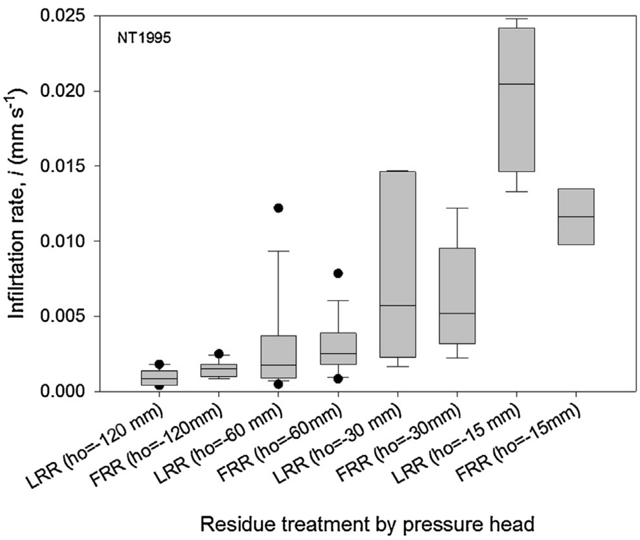

Fig. 3. Effect of residue management, Full Return Rate (FRR) or Low Return Rate (LRR), on the distribution of infiltration rates at four levels of surface water pressure potential (h_o). The horizontal black bar inside the box represents the median infiltration rate for a no-till system (NT1995). The bottom of the box and the top of the box represent the 25th and 75th percentiles, respectively. Lines extending vertically from the box represent variability outside the lower and upper quartile range and numerically represent the 10th and 90th percentiles, respectively. Data points outside the bottom 10% or above the top 90% are plotted as individual closed black circles.

the Full Return Rate. In the NT1995 field corn yields were similar for the two return rate treatments with an overall average of 7.9 Mg ha^{-1}. During the corn phase the Full Return Rate returned an averaged 7.33 ± 0.28 Mg stover ha^{-1} yr^{-1} while on average 1.57 ± 0.22 Mg stover ha^{-1} yr^{-1} was returned in the Low Return Rate. Soybean grain yield was 3.13 Mg ha^{-1} yr^{-1} in Full Return Rate but was significantly less, 2.88 Mg ha^{-1} yr^{-1} in the Low Return Rate. Although soybean grain yield was reduced by the residue return treatment, the straw production was not, such that on average of 4.6 ± 1.3 Mg soybean residue ha^{-1} yr^{-1} was returned. At planting in the NT1995 field, the percentage of soil covered with residue ranged from ~40% for the Low Return Rate to ~70% at the Full Return Rate.

3.2. Soil base line

The two fields had similar base line properties (Table 1). In the Chisel field, bulk density in the 0–20 cm depth increments was <1.30 Mg m^{-3}, below this depth had higher bulk density. Surface soil pH was near neutral over-laying alkaline pH subsoil with similar sand and clay content with depth. Textural composition (sand and clay) was similar at all depths. In the NT1995, the bulk density in the 0–20 cm range was about 1.4 Mg m^{-3}, below which it increased to as high as >1.58 Mg m^{-3}. Surface soil pH was near neutral over-laying alkaline pH subsoil. In both fields, Johnson et al. (2013) reported bulk density measured in 2010 was similar to baseline and did not differ among residue treatments. In both fields, soil organic C declined with depth, with increasing inorganic C concentration, especially below 30 cm.

3.3. Tension infiltrometer measurements

In order to envision the effect of residue return on surface soil water infiltration, plots of i for different values of h_o are presented in Fig. 1. Although these data do not represent the entire data set collected, they were selected as representative of the results observed. Initial infiltration rates for the Chisel Full Return Rate h_o treatments varied by factors of 2–5 whereas the initial infiltration rates for the Chisel Low Return Rate treatments were nearly identical (Fig. 1a, b). Both Chisel residue return data sets exhibit i that decrease rapidly at first, then approach sensibly constant asymptotic infiltration-capacity values. Initial infiltration rates for NT1995 Full Return Rate and Low Return Rate exhibited similar trends as the Chisel experiment (Fig. 1c, d). These data further show that Full Return Rate and Low Return Rate treatments approach similar infiltration-capacity values at h_o between −120 and −30 mm. In contrast, the infiltration-capacity value decreased by a factor of 10 between the two NT1995 residue return treatments at h_o = −15 mm (h_{-15}) (Fig. 1c, d).

Box-and-whisker plots of non-transformed data were used to show the distribution of infiltration rates from each tillage experiment (Fig. 2 and 3). In each box plot the horizontal black bar inside the box represents the median infiltration rate. The bottom of the box and the top of the box represent the 25th and 75th percentiles, respectively. Lines extending vertically from the box represent variability outside the lower and upper quartile range and numerically represent the 10th and 90th percentiles, respectively. Data points outside the bottom 10% or above the top 90% are plotted as individual closed black circles.

For Chisel field experiment, the data exhibited an increasing trend in median i as h_o became less negative (Fig. 2). Median i values were similar between residue return treatments for h_{-120} to h_{-30}, however, the data showed increased variation in median i between residue return treatments for h_{-15} (Fig. 2). In general, box plots for residue return treatments and h_o share a common level of symmetry, observed by similarity in box size, between residue return treatments (Fig. 2). The comparative shortness of box plots for h_{-120} and h_{-60} indicates that i between Chisel Low Return Rate and Full Return Rate treatments had similar distributions. In contrast, the comparative tallness of box plots for h_{-30} and h_{-15} indicates that i between Chisel Low Return Rate and Full Return Rate treatments had broader distributions. Finally, the box for Low Return Rate h_{-30} was asymmetrical about the median and exhibited positive skewness (Fig. 2).

Box plots for the NT1995 field experiment exhibited an increasing trend in i as h_o became less negative (Fig. 3). Median i values were similar between residue return treatments for h_{-120} to h_{-30}, however, the data show increased variation in median i between residue return treatments for h_{-15} (Fig. 3). NT1995 box plots for residue return treatments and h_o were noticeably asymmetric, as observed by dissimilarity in box size, with the exception of h_{-120} (Fig. 3). The comparative shortness of box plots for h_{-120} and h_{-60} indicates that i between NT1995 Low Return Rate and Full Return Rate treatments had similar distributions. The contrast in box size of box plots for h_{-30} and h_{-15} indicates that i between NT1995 Low Return Rate and Full Return Rate treatments had broader distributions. The difference in height between box plots at h_{-15} suggests potential differences between residue-return treatments for i (Fig. 3). Finally, the box for Low Return Rate h_{-30} was asymmetrical about the median and exhibited positive skewness while the box for Low Return Rate h_{-15} was asymmetrical about the median and exhibited negative skewness (Fig. 3).

3.4. Hydraulic conductivity function

Summary of the unsaturated hydraulic conductivity as a function of h_o are shown in Fig. 4. The analytical solution for obtaining $K_{(h)}$ uses two steady-state infiltration rates from different tension infiltrometer supply pressure heads to estimate $K_{(h)}$ at the midpoint of an interval between two successively applied pressures heads (Ankeny et al., 1991). Jarvis and Messing (1995) further estimated $K_{(h)}$ for the largest and smallest tension infiltrometer supply pressure heads by assuming the values of

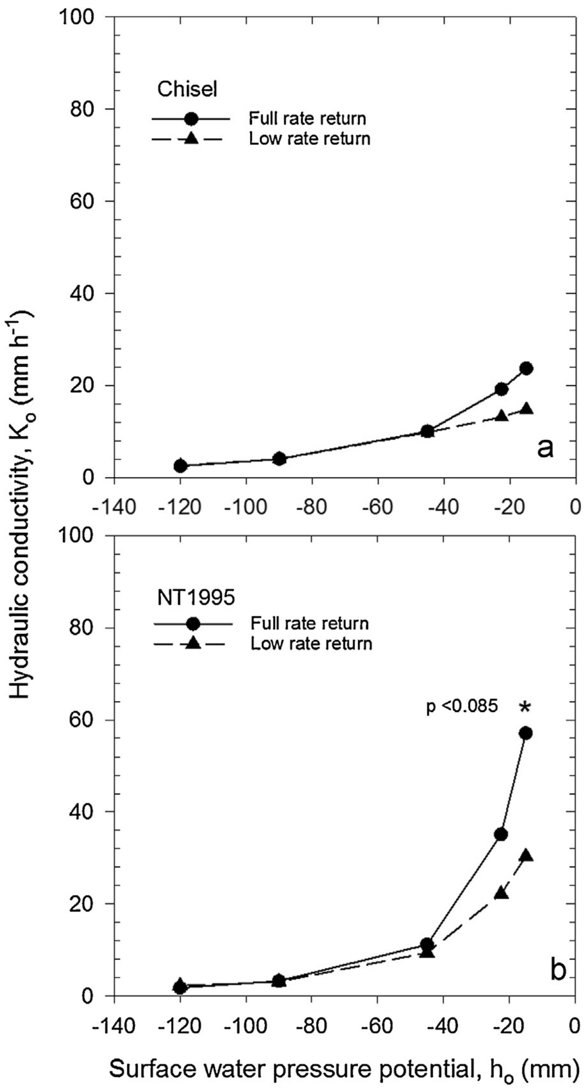

Fig. 4. Mean hydraulic conductivity functions, (K_o), at surface pressure potentials for two levels of residue management, Full Return Rate (FRR) and Low Return Rate (LRR), from (a) chisel plow field (Chisel) and (b) no-till field (NT1995).

constant a to be equal to $a_{3/2}$ and $a_{n-1/2}$, respectively, where n is the number of supply pressure heads. The $K_{(h)}$ function represents an average $K_{(h)}$ derived from replicate infiltrometer measurements for each tillage system and residue management treatment. For the Chisel field experiment, Low Return Rate and Full Return Rate were comparable; there was no effect of residue removal on $K_{(h)}$ (Fig. 4a). Unsaturated hydraulic conductivity ranged from 3 to 15 mm h^{-1} for Low Return Rate and 3–24 mm h^{-1} for Full Return Rate.

For the NT1995 field experiment, Low Return Rate and Full Return Rate were comparable for $K_{(h)}$ between h_{-120} and h_{-45} (Fig. 4b). Strong non-linearity of $K_{(h)}$ with decreasing surface water potential reveals a distinct transition in $K_{(h)}$ between h_{-45} and h_{-15} (Fig. 4b). Unsaturated hydraulic conductivity ranged from 2 to 30 mm h^{-1} for Low Return Rate and 2–57 mm h^{-1} for Full Return Rate. Between h_{-45} and h_{-15}, a distinct increase in $K_{(h)}$ was observed for both residue removal treatments. Such a relative change in hydraulic conductivity indicated the initiation of condition or rapid transmission of water through pores or structural voids with a relatively large cross-sectional area. A comparison of Full Return Rate and Low Return Rate indicated that $K_{(h)}$ at h_{-15} was significantly different ($p < 0.1$) by a factor of 1.7 when all stover was returned at this field. These data suggest that there are more actively conducting large pores in the Full Return Rate treatment at h_{-15} for its $K_{(h)}$ to be greater than that of the Low Return Rate treatment.

3.5. Sorptivity

Sorptivity deduced from unsaturated, unconfined, steady-state water infiltration measurements is shown in Fig. 5. The S_o function represents an average S_o derived from replicate infiltrometer measurements for each field and residue management treatment. No significant difference in S_o was observed between residue return rate treatments in the Chisel field (Fig. 5a). Sorptivity at all levels of surface water potential was relatively uniform and exhibited a linear trend. These data indicate that this soils ability to absorb water under chisel tillage, regardless of residue return rate, involved soil pores or voids of similar size and frequency. In addition, water did not likely enter large soil pores or voids during infiltration under these negative surface water pressure potentials in the Chisel field. The apparent slight increase in S_o from h_{-60} to h_{-30} followed by a slight decrease from h_{-30} to h_{-15}, which was not statistically significant, was consistent for both Full Return Rate and Low Return Rate (Fig. 5a).

For the NT1995 field, Full Return Rate and Low Return Rate treatments were comparable for S_o between h_{-120} and h_{-45}; there was no effect of residue return on S_o (Fig. 5b). Strong non-linearity of S_o with decreasing surface water potential reveals a distinct transition from h_{-60} to h_{-30}. The difference in S_o was significantly different ($p < 0.1$) between Full Return Rate and Low Return Rate at h_{-15} for this site. Based on the difference in S_o between Full Return Rate and Low Return Rate, the Full Return Rate treatment had greater pore volume filled at a surface water potential of h_{-15}.

3.6. Microscopic length

The microscopic length scale or characteristic mean pore size, λ_m, is shown in Fig. 6. For a given h_o, λ_m is an indicator of whether capillarity or gravity is the dominant mechanism of water transmission into the soil. Between residue removal treatments, a comparatively large λ_m indicated an active network of macro-pores. Microscopic length scale in the Chisel field experiment for both levels of residue return was less than 150 μm (Fig. 6a). There was no consistent trend observed from the data and they were variable, ranging from 10 to 149 mm. The values of λ_m for the Chisel field indicated that the active network of pores had small radii and accordingly water flux was controlled by capillarity.

The relationship of λ_m and h_o for the NT1995 field experiment indicated a gradual increase in λ_m for both residue return rate treatments as h_o approached saturation (Fig. 6b). This behavior indicated that the functional pore network involved in water transmission was shifting from capillary to gravity dominated flow. Active pores had small radii at h_{-120} for both Full Return Rate and Low Return Rate indicating that water flux was controlled by capillary pores of the soil matrix. The increase in λ_m with h_o between h_{-120} and h_{-60} indicated the transition from capillary dominated flow to gravity dominated macropore flow. At this site, residue return rate affected λ_m for h_{-30} where there was a statistically significant increase in λ_m for Full Return Rate compared to Low Return Rate (Fig. 6b).

3.7. Aggregate distribution, erodible fraction and aggregates stable in water

Harvesting corn stover changed DASD (Table 2). Soil collected from the Chisel field, only about 15% of the soil sample was in macro-aggregates or small clods too large to pass the 20 mm sieve. The Full Return Rate treatment increased (13%) the fraction of

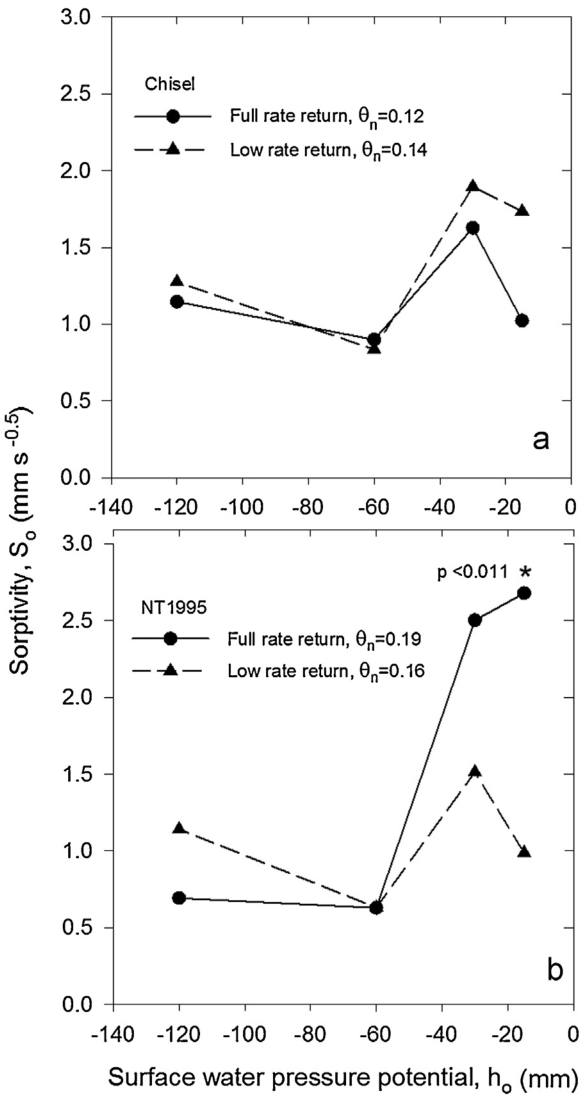

Fig. 5. Mean sorptivity, (S_o), at surface pressure potentials for two levels of residue management: Full Return Rate (FRR) and Low Return Rate (LRR) from (a) chisel plow field (Chisel) and (b) no-till field (NT1995). Initial volumetric water content θ_n was determined in close proximity but outside the point of infiltrometer measurements.

aggregates in the 9–20 mm size-classes, but decreased (4–13%) the fraction of dry aggregates in the three smallest size-classes. In the NT1995 field, 0.28 g kg^{-1} (Low Return Rate) to 0.41 g kg^{-1} (Full Return Rate) was too large to pass through the 20 mm sieve. In the Low Return Rate, the smallest size-class had 24%, 35% and 41% greater fractions than the corresponding size-classes from the Full Return Rate. The shift in DASD was reflected in MWD and the erodible fraction.

Harvesting corn stover significantly reduced MWD and increased the erodible fraction of aggregates in both fields (Table 3). In the Chisel field, MWD declined about 8% in the Low Return Rate compared to the Full Return Rate treatment. In the NT1995 field, the decline between the Low Return Rate compared to the Full Return Rate treatment was 16%. A reduction in MWD means there is more soil mass within the smaller aggregate size classes with a declining number of larger heavier aggregates. For the Chisel field, the erodible fraction of aggregates increased 20% in the Low Return Rate compared to the Full Return Rate treatment. For the NT1995 field, the erodible fraction of aggregates increased 40% in the Low Return Rate compared to the Full Return Rate treatment. Also from NT1995 field, the fraction of ASW was reduced 10, 8.5 and 11% in the Low Return Rate compared to the Full Return Rate treatment for aggregate size groups 1–2, 2–3, and 3–5 mm, respectively (Table 4). Collectively, the MWD, EF, and ASW results are evidence that the aggregates are less stable resulting in a shift toward more small aggregates at the expense of larger aggregates when stover is not returned to the soil.

4. Discussion

Factors affecting soil *i* and infiltration capacity are affected primarily by two groups of factors: abiotic, soil and soil profile characteristics and biotic features. Abiotic factors include such elements as soil texture, soil mineralogy and soil structure/aggregation. Biotic factors include root channels, earthworm and insect burrows and perforations and finally plant residues. These factors in turn influence other soil hydrologic properties.

4.1. Hydraulic conductivity function

Our measurements of $K_{(h)}$ at the soil surface in the soil water pressure potential range from h_{-15} to h_{-120}, under Chisel tillage management, for two residue management treatments, Low Return Rate and Full Return Rate, indicate a relatively uniform network of actively conducting pores. The hydraulic conductivity for the two residue management conditions changed very little over the measured pressure potential range. The lack of difference in $K_{(h)}$ between Low Return Rate and Full Return Rate apparently had less to do with residue management intensity and more to do with soil disturbance as a result of annual tillage and consolidation of the soil surface following planting and normal precipitation. Differences in $K_{(h)}$ can also be attributed to soil consolidation after tillage due to in-washing of fine soil particles into pores or structural voids, the breakdown of micro-aggregates or the swelling soil colloids. Tillage often loosens the surface soil consequently decreasing bulk density and increasing $K_{(h)}$. Measurement of bulk density for the top 10 cm of soil is in agreement with this concept (Table 1). However, $K_{(h)}$ in this experiment does not follow this pattern. Although bulk density measurements made in the fall of 2010 did not differ from base line or by treatment (Johnson et al., 2013), it is possible that previous bulk density measurement did not represent 2012 Low Return Rate and Full Return Rate treatments.

For the top 0–10 cm, bulk density for this no-till experiment ranged from 1.37 to 1.41 Mg m^3 (Table 1). In 2010, Johnson et al. (2013) reported that bulk density in these plots was similar to baseline and did not differ among residue return treatments. Although this range indicates soil consolidation and consequently smaller hydraulically active pores, $K_{(h)}$ suggests hydraulically active pores or structural voids. A hydraulically active pore system under no-till can be attributed to reduced soil sealing encouraged by residue cover.

In the NT1995 Field for Low Return Rate and Full Return Rate, measurements of $K_{(h)}$ at the soil surface indicate a bimodal network of actively conducting pores. The data showed a rapid increase in $K_{(h)}$ between h_{-45} and h_{-15}. The difference in $K_{(h)}$ between Low Return Rate and Full Return Rate was attributed to residue management intensity where $K_{(-15)}$ was nearly twice as great for the Full Return Rate condition compared to the Low Return Rate. Soil properties more conducive to run off than to infiltration, can result in less water available for crop production (Baumhardt et al., 2012; Langhans et al., 2011), as may occur from Low Return Rate. Whereas, under conditions with no soil disturbance, hydraulically active pores are able to transmit water into the soil profile and away from the soil surface. Under this condition it is likely that precipitation has a higher likelihood of entering the soil profile rather than possibly being lost to surface

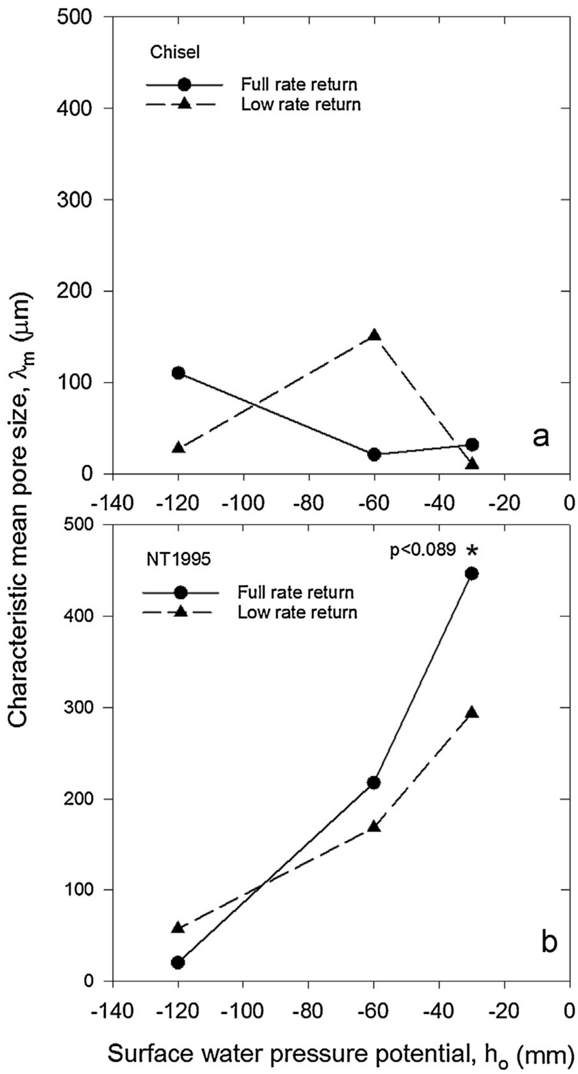

Fig. 6. Mean microscopic length, (λ_m, mean pore diameter), at surface pressure potentials for two levels of residue management Full Return Rate and Low Return Rate from (a) chisel plow field (Chisel) and (b) no-till field (NT1995).

runoff. A potential reduction in surface runoff could also reduce the incidence of soil erosion. Global climate changes are anticipated to increase the probability of both extreme rainfall events and drought conditions; thereby, challenging soils' resilience (Walthall et al., 2012). Under such extreme weather variability, (e.g., incidences of excess and limited precipitation) increased surface hydraulic conductivity, which could limit runoff and erosion and potentially increase soil water storage for crop uptake.

Table 2
Distribution of dry stable aggregates. Material >20 mm that did not pass through the screen into the rotary sieve.

Size-Class mm		0–0.5	0.5–1	1–2	2–3	3–5	5–9	9–20	>20
Field	Return Rate	g g^{-1}							
Chisel	Full	0.11	0.10	0.12	0.09	0.09	0.13	0.19	0.15
	Low	0.13	0.11	0.13	0.09	0.08	0.12	0.16	0.16
	p	0.05	0.007	0.01	ns	ns	ns	0.01	ns
NT1995									
	Full	0.07	0.05	0.07	0.07	0.07	0.10	0.16	0.41
	Low	0.11	0.08	0.09	0.07	0.07	0.10	0.18	0.28
	p	0.0001	0.0001	0.08	ns	ns	ns	0.06	0.02

4.2. Sorptivity

Sorptivity is a hydrodynamic soil property used to characterize the separation of water flow between the less mobile soil matrix and very conductive structural voids and pores during early times of infiltration. Measurements of S_o at the soil surface, in the h_o range from h_{-15} to h_{-120}, under chisel tillage management, Chisel experiment, showed that S_o for the two residue management conditions changed very little over the measured pressure potential range (Fig. 5a). Overall S_o values for Low Return Rate and Full Return Rate over the measured pressure potential range suggest that the flow domain is dominated by small, less conducive pores. The slight decrease in S_o from h_{-30} to h_{-15} could be attributed to one of several factors. This result could be explained by a lack of interconnected relatively large pores or structural voids, detachment followed by deposition of soil particles that obstructed hydraulically active pores, or loss of hydraulically connected pores due to soil reconsolidation after cultivation, seedbed preparation and planting or due to swelling of soil colloidal particles.

Measurements of S_o at the soil surface under no-till, NT1995, showed that S_o for Full Return Rate and Full Return Rate changed very little at relatively high pressure potentials h_{-120} and h_{-60} (Fig. 5b). In contrast, S_o values for Low Return Rate and Full Return Rate increased non-linearly over surface pressure potentials h_{-30} and h_{-15}. Initially, under pressure potentials h_{-120} and h_{-60}, the data indicated that large pores (e.g. macropores) that drain at relatively large pressure potentials had little influence on S_o. In contrast, for h at successively lower potentials, the data indicated that the flow domain was affected by flow into relatively large pores created by root channels, biopores or structural voids or due to a high level of pore continuity within the existing pore network. The significant difference in S_o between Low Return Rate and Full Return Rate at h_{-15} is attributed to residue management. This data suggests that under conditions where the maximum amount of residue is returned to the soil surface, increases in soil water transmission from rapidly conducting pores to the soil matrix could lead to increased soil water storage and plant available water during the growing season. Work in eastern Colorado revealed comparable results in that returning more crop residue increased the fraction of macro-aggregates, rate of infiltration, and plant available water (Shaver et al., 2002).

4.3. Microscopic length

Measurements of λ_m at the soil surface in the pressure potential range from h_{-15} to h_{-120}, under chisel plow tillage management, for Low Return Rate and Full Return Rate was characterized by a narrow range of "mean" pore sizes (Fig. 6a). Such a narrow range of pores size is not unexpected considering the annual cycle of homogenization of the surface soil due to tillage, which is in agreement with the $K_{(h)}$ results. The values of λ_m suggest that the hydraulically active pores regardless of residue management appear to have relatively small radii across the measured pressure potential range for this chisel plowed soil. The general decreasing trend in λ_m suggests that some fraction of the hydraulically active pore system is isolated and does not participate in flow due to soil settling after planting and/or precipitation events (Fig. 6a).

The NT1995 field for Low Return Rate and Full Return Rate, measurements of λ_m at the soil surface in the pressure potential range from h_{-15} to h_{-120}, were characterized by a wide range of mean pore sizes (Fig. 6b). At both return rates, functional pores have small radii for values of h_{-120} indicating that water flux is controlled by capillary pores within the soil matrix. Gradually, λ_m increases as h_o decreases, which indicates the hydraulically active pore network is shifting from capillary to gravity dominated flow.

Table 3
Mean weight diameter (MWD) and erodible fraction (EF) measured in two field experiments calculated from those aggregates within 0–9 mm Size-classes.

	Chisel			NT1995		
	Return Rate			Return Rate		
	Full	Low	P	Full	Low	P
MWD (mm)	2.80 a[†]	2.58 b	0.0014	3.17 a	2.66 b	0.0001
EF ($g\,g^{-1}$)	0.25 b	0.29 a	0.0016	0.19 b	0.26 a	0.0001

[†] Values followed by different letters differed at $P \le 0.05$ within a field.

The increase in λ_m at h_{-30} indicates that gravity dominated flux due to a network of relatively large pores is facilitating rapid transmission of water into the soil. At h_{-30} the value of λ_m for Full Return Rate was statistically greater than Low Return Rate, which indicated that residue return rate treatments affected λ_m (Fig. 6b).

4.4. Interaction between hydraulic and physical properties

Improved hydrologic properties (i.e., $K_{(h)}$, S and λ_m) are consistent with the increased MWD, reduced EF found in the Full Return Rates, which is especially evident in the NT1995 field. Although, differences in total soil organic carbon were not detected between the residue return treatments, particulate organic matter was 22% lower in Low Return Rate treatment compared to Full Return Rates (Johnson et al., 2013). The decline in particulate organic matter suggests SOC level are changing, since MWD is positively correlated with soil organic carbon (Das et al., 2014). Therefore, a decline in MWD may also predict a decline in soil organic carbon. Tillage in the Chisel field overshadowed impacts of stover return treatments. Osborne et al. (2014) reported returning stover resulted in fewer aggregates in the EF and a larger MWD indicative of more macro aggregates consistent with large pores resulting in more rapid infiltration. Larger more stable aggregates, which are more resilient to water and wind, coupled with improved infiltration, likely lead to lower runoff and less erosion.

Measurements of soil hydraulic properties relating to the process of infiltration are necessary and important to understanding preponding conditions and for the capacity to predict time to incipient ponding and runoff. Erosion removes valuable, nutrient rich topsoil, which when displaced into waterways or airborne is detrimental to water and air quality. When incipient rain infiltrates into the soil it can enter the soil matrix where it will remain unless the soil profile becomes saturated and it leaches, or until it can leave the profile via evapotranspiration. Alternatively, as some of the data from the NT1995 experiment suggests, soil conditions may exist in which the network of interconnected pores in the soil profile may not retain water but rather precipitation may actually drain down the profile bypassing the soil matrix and may not be plant available. Our study was not designed for a complete water balance, but increased infiltration data supports the likelihood that rainwater can be used to support crop growth or could be available for leaching under suitable conditions.

Table 4
Fraction of stable dry aggregate within a size group that remained stable in water (ASW) from NT1995 field experiment.

Aggregate size group (mm) Treatment	NT1995 field experiment 0.5–1 ASW ($g\,g^{-1}$)	1–2	2–3	3–5	5–9
Full return rate	0.53	0.53 a[†]	0.53 a	0.57 a	0.60
Low return rate	0.49	0.48 b	0.48 b	0.51 b	0.54
p	ns	0.03	0.04	0.02	ns

[†] Values followed by different letters within an aggregate size group differed at $P \le 0.05$.

5. Conclusions

In Chisel field, impacts of residue return rate on hydrological measures were equivocal, with both treatments having low infiltration. The low infiltration rate, coupled with exposed soil surface and smaller and less stable aggregates, indicates the field is at greater risk for wind and water erosion events. In the NT1995, hydrological measurements at Low Return Rates suggest soil at greater risk for run-off and associated soil erosion. In contrast, the NT1995 hydrological measurements at Full Return Rates suggest soil maybe more resilient to rainfall extremes. The results of this study support the recommendation to return stover on tilled fields. The results also showed that even without tillage a low residue rate can degrade soil properties.

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